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CANOPY AND STEM STIFFNESS CONTRIBUTIONS TO DISEASE RESISTANCE IN LENTIL

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ABSTRACT

Lentil (*Lens culinaris* L.) cultivars similar to Laird, in the large green market class, are currently produced in Western Canada and are susceptible to lodging. The first goal of this study was to identify characteristics of lentil canopy architecture that will lead to reduced lodging and improved yield. The second goal was to determine if plant traits associated with lodging exist to allow indirect selection of lodging resistant material early in a breeding program. Four stiff-stem unadapted genotypes from the International Center for Agricultural Research in the Dry Areas, Syria, varying in leaf size and canopy openness were compared to large green and other locally adapted cultivars at three population densities in the field in 2001 and 2002. Canopy measurements included biomass and light interception at weekly intervals, recovery from stem bending, recovery from canopy crushing, lodging score, end of season harvest index, yield, maximum height, final branch number, stem fiber and lignin content. Cultivars adapted to Saskatchewan had greater biomass (525 to 700 g m^{-2}), higher seed yield (96 to 130 g m^{-2}), higher maximum light interception (61 to 80%), higher final branch number (17 to 19), and greatest overall plant height (0.3 to 0.44 m), but large green cultivars with canopy development similar to Laird had weak stems and were more prone to lodging. CDC Milestone and Crimson had improved canopy architecture compared to large green cultivars with higher harvest index (0.40, 0.34 respectively compared to <0.26 for large green cultivars) and 30% lower lodging. Unadapted genotypes produced less biomass (325 to 475 g m^{-2}) and had reduced lodging compared to locally adapted cultivars. Unadapted genotype 2000-7L performed most similarly to the adapted genotypes with the highest biomass (476 g m^{-2}), branch number (18), height (0.30 m), maximum light interception (56%), and yield (53 g m^{-2}) of the unadapted genotypes, and was the second lowest lodging in 2001. Line 96-47L appears to be the best unadapted genotype candidate for crossing to improve lodging resistance but yield is lowest. Highly variable weather conditions between 2001 and 2002 resulted in inconsistent lodging data, and 2001 data appeared to be the most representative of genotypic differences. Plant traits associated with lodging score, namely recovery from stem bending, recovery from canopy crushing, stem diameter, stem fiber and lignin content, were assessed as alternate measures of lodging. Stem diameter was found to be the best method because genotypic ranking across locations was consistent. Multiple linear regressions of both lodging score and stem diameter resulted in the highest proportion of variability being explained for stem

diameter ($R^2 = 0.78$). Stem diameter was a function of all the following measurements: branch number, recovery from canopy crushing, plant density, height, fiber and lignin content. Lentil appears to use a combination of phloem and lignin tissues and fiber for stem thickness. The use of stem diameter as an alternative measurement of lodging resistance in a breeding program will limit environmental influence, allowing selection based on a few plants early in the breeding program, thereby reducing time and cost.

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EXECUTIVE SUMMARY

"Canopy and stem stiffness contributions to disease resistance in lentil" was jointly funded by Saskatchewan Pulse Grower Association and Saskatchewan ADF. Germplasm from the International Center for Agricultural Research in the Dry Areas, (ICARDA), in Aleppo, Syria and other Mediterranean environments exhibit a range in stem stiffness, degree of branching, and maturity which can be exploited to develop large green lentil cultivars better suited to Saskatchewan soil zones and environmental conditions. A change in canopy architecture, increased stem stiffness and a more efficient harvest index can greatly improve flexibility in production and increase yield and seed quality (Austin et al., 1980). Late-season disease incidence can be reduced and managed at the same time.

Project Objectives

1. To assess the effect of canopy structure (stiffness, degree of branching, canopy aeration) on disease development at varying population densities.
2. To fit lentil production systems for the large green lentil class to specific soil zones and length of growing season through optimal crop architecture and stem stiffness.
3. To assess growth potential of germplasm and crosses for improved biomass, harvest index, yield and quality at varying population densities.

Methods

Three target population densities (60, 100 (current recommendation) and 140 plants m^{-2}) of lentil were seeded at two experimental locations in 2001: Vanscoy in the dark brown soil zone; and Rosthern in the thin black soil zone. In 2003, Saskatoon, Outlook and Moose Jaw locations were used because we had irrigation access to reduce drought effects. Eight different lentil genotypes were seeded at each population density:

CDC Grandora (Large Green Lentil class)
CDC Plato (formerly 964a-4) (Large Green Lentil class)
CDC Milestone (smaller plant but has higher harvest index and greater yield than Laird, Large Green Lentil class)
Crimson (red lentil with lodging problems)
FLIP 96-47L (stiff-stem with open canopy)
FLIP 2000-6L (narrow leaf)
FLIP 96-25L (stiff-stem and narrow leaf)
FLIP 2000-7L (stiff-stem and bushy canopy)

Four replications per location were used, for a total of 96 plots. A second set of plots was seeded at Vanscoy and Rosthern in 2002, and at Moosejaw and Outlook in 2003. Each location control plots were to be

sprayed at any sign of canopy disease. Weeds were controlled through use of post-emergence herbicides and hand weeding

Measurements for phenotypic traits included:

- Stand count at seedling emergence.
- The above ground biomass was measured at four stages during the plant growth period (canopy closure, flowering, start of pod fill, and physiological maturity).
- Stem stiffness ratings at start of pod fill and at physiological maturity.
- Light interception at weekly intervals to assess canopy development and openness.
- Plant height at physiological maturity.
- Harvest index at end of season on a sub sample of plants per plot.
- Final harvest yield.
- Lodging and disease scores.

Results

The summer field season in 2001 was hot and dry, and no disease was found in the disease set of plots. Plots were both *Ascochyta* and *Anthracnose* free. Limited disease was seen at Saskatoon and Outlook in 2002. No disease was found in 2003. The locations and years were combined as environments.

- Cultivars adapted to Saskatchewan had greater biomass, higher final branch number, greatest overall plant height and highest yield.
- Large green cultivars with canopy development similar to Laird had weak stems and were more prone to lodging.
- Two FLIP lines (96-47L; 2000-6L) had less branching and lowest overall plant height, resulting in less biomass and reduced lodging compared to locally adapted cultivars.
- The other two FLIP lines (96-25L; 2000-7L) had intermediate canopy characteristics, but were overall the best FLIP candidates for crossing based on harvest index, least lodging, most branching and similar yield.
- Crimson and CDC Milestone responded similarly to FLIP genotypes, but were more similar to the large green cultivars for lodging and biomass.
- CDC Milestone and Crimson had improved canopy architecture compared to large green cultivars.
- CDC Milestone had highest harvest index and the Laird types had the lowest harvest index.
- Reduced branching may be useful traits to help reduce lodging. All FLIP lines had less branching than CDC Plato and CDC Grandora.
- Stem diameter was the most consistent and effective lodging measurement in lentil.

Conclusions

Drought conditions in both 2001 and 2002 resulted in reduced canopy growth for all eight genotypes tested compared to a growing season with average to above average rainfall and minimal disease incidence.

The timing and severity of environmental conditions was highly influential on plant lodging. The 2001 lodging data were most representative of actual plant lodging and genetic differences in ability of lentil to resist lodging were most evident in these results. In 2001, the unadapted genotypes with the stiff-stem trait were the least susceptible to lodging, while the large green lentil genotypes lodged the most. In 2002, lodging was influenced by the harsh rain and windstorms that occurred in August, conditions that most affected the early maturing unadapted genotypes. In 2002, no plant population treatment effects were observed, whereas in 2001 lodging increased with higher plant populations. Overall, this would suggest that lodging patterns in 2001 were typical of rainfall distribution from historic weather patterns for Saskatchewan, and that 2002 plant lodging was an atypical effect more closely related to plant maturity and weather influence.

We hypothesized that a canopy better able to recover from being crushed would have greater stem resiliency, and thus a greater ability to withstand lodging. However, a positive association between recovery from crushing and lodging suggested that as a canopy's ability to recover from crushing increased, lodging increased, an association likely driven by high biomass. The greater the aboveground biomass produced by a lentil canopy, the greater the ability to withstand crushing, and the higher the canopy recovery, but a high risk of lodging.

The greater the fiber content in the plant stems (ADF, NDF), the more biomass and, surprisingly, the more likely lodging is to occur. Lignin (ADL) was more difficult to interpret. Stem diameter may be the best plant trait associated with lodging because in both years, genotype ranking by stem diameter was consistent. This would suggest that although stem diameter is plant population density dependent, ranking of genotypic variability is consistent across each plant population. Any measurement position on the bottom half of the plant could be used for determining the stem diameter ranking of genotypes, as long as it was consistently used, and taken at mid to the end of season.

In 2001, as much as 78% of stem diameter variability could be explained by the following canopy traits: final branch number, recovery from canopy crushing, plant density, final plant height, NDF, ADF, and ADL. Overall, lodging results from 2001 suggest that as stem diameter is increased, the plants susceptibility to lodging is also increased. In 2001, CDC Plato and CDC Grandora had the largest stem diameters and were most susceptible to lodging, and 96-47L had the smallest diameter of stem and the greatest lodging resistance. Therefore, for screening lodging resistance in crosses made from a lodging resistant genotype (e.g. 96-47L) and a highly lodging susceptible genotype (e.g. CDC Grandora or CDC Plato), selection of progeny with the smallest stem diameters should be the most lodging resistant. For a higher yielding lodging-resistant parent, other FLIP lines may be a better choice. We recommend 2000-6L followed by 96-25L from results in this report. Crosses between locally adapted cultivars and several FLIP lines have been made to improve lodging resistance in future cultivars.

Plant lodging is a complex trait influenced by agronomic management, genotypic variability, and the environment. In a breeding program, environments vary from location to location and year to year, making selection for lodging tolerance difficult, and lodging score is not a consistent measurement. The use of stem diameter, on only a few plants sub-sampled per plot, would be an effective indicator of lodging resistance, reducing time and cost. Late season branch number is another simple and fast measurement to make, requiring a few plants per plot at the end of a season.

Implications for the CDC Pulse breeding program

Crosses have been made between CDC Milestone and several FLIP lines to incorporate the stiff stem trait. Breeding is in progress to select the best adapted progenies from these crosses for Saskatchewan.

TECHNICAL REPORT

1. Background

The large green lentil market class (the cultivar Laird and related varieties) has accounted for more than 50% of Canada's seeded lentil production area for almost 25 years. Annual value of this lentil crop is approximately $ 200 million. However, significant economic losses occur in large green lentil due to (1) late-maturity and poor productivity in "adapted areas" (Dark Brown soil zone) when above average precipitation and cool weather occur in late July, and (2) via loss in quality associated with lodging and moisture retention in the canopy. Productivity is also consistently poor in average years in the Thin Black and Black soil zones. Yield losses occur through low harvest index (poor partitioning of biomass to yield), lodging, and disease infection of stems, leaves and seeds. Lush canopies increase the probability of disease spread in wet years. New cultivars are now resistant to foliar pathogens like *Ascochyta*, and even *Anthracnose* (CDC Robin), resulting in a shift to late-season pathogens like *Sclerotinia* and *Botrytis*. We intend to develop a lentil management strategy using canopy modification as the major tool. Recently, the CDC lentil breeding program has acquired a range of stiff stem germplasm from the International Center for Agricultural Research in the Dry Areas, (ICARDA), in Aleppo, Syria, which offers the potential to alter the structure of the plant canopy to improve aeration, reduce humidity and reduce disease, while optimizing biomass and harvest index.

2. Project Objectives

We propose advancing large green lentil production through improved canopy development and yield partitioning along with disease resistance, giving growers more flexibility in production and higher yield potential. Specific objectives were:

1. To assess the affect of canopy structure (stiffness, degree of branching, canopy aeration) on disease development at varying population densities.
2. To fit lentil production systems for the large green lentil class to specific soil zones and length of growing season through optimal crop architecture and stem stiffness.
3. To assess growth potential of germplasm for improved biomass, harvest index, yield and quality at varying population densities.

For year 1 and 2 we evaluated biomass, harvest index, canopy architecture and disease incidence of lentil genotypes grown at three population densities in several soil zones (brown, dark brown, moist dark brown, black), with limited disease and without disease presence. For year 3 we evaluated biomass, harvest index, canopy

architecture, disease incidence of lentil genotypes grown at three population densities in two soil zones (moist dark brown, black) without disease presence due to drought.

3. *Materials and Methods*

Three target population densities (60, 100 (current recommendation; Saskatchewan Pulse Growers, 2000) and 140 plants m^{-2}) of lentil were seeded at two experimental locations in 2001: Vanscoy in the dark brown soil zone; and Rosthern in the black soil zone. In 2002, Saskatoon, Outlook and Moose Jaw locations (brown, dark brown) were used because we had irrigation access to reduce drought effects. In 2003, an additional Saskatoon location (Pulse Growers Land; dark brown) and Rosthern (black) were used. Eight different lentil genotypes were seeded at each population density:

- CDC Grandora (large green Laird type)
- CDC Plato (large green Laird type)
- CDC Milestone (small green lentil, smaller plant but has higher harvest index and greater yield than Laird)
- Crimson (red lentil with lodging problems)
- FLIP 96-47L (unadapted with stiff-stem, open canopy, and very early maturity)
- FLIP 2000-6L (unadapted with narrow leaf and early maturity)
- FLIP 96-25L (unadapted with stiff-stem, narrow leaf, and early maturity)
- FLIP 2000-7L (unadapted with stiff-stem and bushy canopy)

The ICARDA genotypes, designated by FLIP, represented the range of stem stiffness, branching, and aerated canopy combinations.

Plots would have been sprayed with fungicide to minimize *Ascochyta*, *Anthracnose*, *Botrytis* and *Sclerotinia* (Rovral, Benlate, or Ronilan). However, due to abnormally dry weather conditions, disease was minor or minimal at the end of the growing season and in-season spraying was not used.

3.1. Measurements for phenotypic traits

- Stand count at seedling emergence.
- The above ground biomass was measured at four stages during the plant growth period (canopy closure, flowering, start of pod fill, and physiological maturity).
- Stem stiffness ratings at start of pod fill and at physiological maturity, by holding the tip of a single lentil down to the ground for four seconds, releasing, and measuring the angle at recovery.

- Canopy measurements for openness and stiffness, measured by crushing a fixed area of the lentil plot to half its original height, holding for four seconds, then measuring the compression measured with respect to the original uncompressed canopy height.
- Light interception at weekly intervals to assess canopy development and openness.
- Plant height at physiological maturity.
- Harvest index at end of season on a sub sample of plants per plot.
- Stem sections for fiber analysis and stem diameter measurement.
- Angle bending (bending plant to ground and measuring return angle, FLIPs are stiffer and have greater angles than CDC Grandora).
- Final harvest yield.
- Stem fiber analysis including NDF (neutral detergent fiber), ADF (acid detergent fiber), ADL (lignin).

3.2. Statistical Analysis:

The experimental design was a randomised complete block design with four replications. Eight genotypes were seeded at three population densities for a total of 96 plots in each environment. Nine environments, four in 2001 and five in 2002, were used which covered the range of data. Data collected in 2003 represented severe drought and was not included in the main analysis. At the Vanscoy, Rosthern, Outlook, and Briercrest locations, there were two sets of plots seeded for a disease free (control) and diseased canopy study. One set of plots was a control where if disease pressure existed, fungicide spraying would be used, and a disease set of plots where no spraying would occur. The Saskatoon location was limited to space so only a control set of plots were seeded.

In 2001, Rosthern and Vanscoy plot sizes were 1.4 by 4.9 m, seeded as 10 rows with 0.14 m row spacing. In 2002, Briercrest and Saskatoon plot sizes were 1.4 by 4.9 m, seeded as 10 rows with 0.14 m row spacing. Space was limited at Outlook, so the number of seed rows was reduced to five with 0.14 m row spacing. The plot sizes were 0.7 by 4.9 m.

3.3. Field Procedures

In 2001 and 2002, experimental plots were seeded using a Fabro small plot seeder (Fabro Enterprises Ltd., Swift Current, SK). In 2001, the plots were seeded on May 21 and 22 at Vanscoy and Rosthern, respectively. In 2002, the plots were seed on May 28, 29, and 30 at Briercrest, Outlook, and Saskatoon locations. A granular

formulation of Nodulator® *Rhizobium* inoculant (Becker Underwood Inc., Saskatoon, SK) was placed in the seed rows at 5.65 kg ha^{-1} during the seeding operation.

In 2001, weed control consisted of post-emergent application of sethoxydim (Poast Ultra) and metribuzin (Sencor) at recommended rates, followed by hand weeding. In 2002, pre-planting applications of ethalfluralin (Granular Edge) and glyphosate (Roundup), followed by in-crop herbicide applications of sethoxydim (Poast Ultra) and metribuzin (Sencor) at recommended rates, then hand weeding were used. Grasshopper control in 2003 was done with Lorsban.

Prior to harvesting, plots were sprayed with diquat (Reglone) for complete desiccation.

4. Results and Discussion

4.1. Location summaries

Weather data are summarized in Table 1.

Vanscoy

- Moisture was lacking throughout the growing season (2001), although July rain events were timely for adequate crop growth. The crop was irrigated once (25 mm) in early August.
- Even seed germination and seedling emergence across most of the plots.
- No disease was found in any of the plots, although most plots had full canopy fill.
- Yields were highest for the Control site that had earlier weed removal than the disease.

Rosthern

- Moisture was lacking throughout the 2001 growing season, with less moisture being received compared to the Vanscoy sites.
- The disease site performed better than the control because of earlier weed removal.
- No disease was found in any plots.
- In 2003, drought terminated the trial early.

Briercrest

- Very good moisture in the soil profile at the beginning of the season in 2002.
- The plants grew well, but extreme heat in mid-July affected the overall growth.
- The canopies reached full canopy fill.

- In August, late season rains and wind drove the earlier maturing FLIP cultivars into the ground, while the adapted genotypes were less affected by this, causing variability in the lodging scores.
- Harvest was delayed due to the wet and cool fall, but seed yields declined due to the shelling from the wind and rain and the delay in harvesting.
- The control and disease plots had similar growth and quality.

Outlook

- The plots were grown under irrigation in 2002, canopies filled well and were dense and lush.
- In August, late season rains and wind drove the earlier maturing FLIP cultivars into the ground, while the adapted genotypes were less affected by this, causing variability in the lodging scores.
- Yields were very good as less shelling occurred compared to Briercrest sites.
- The control and disease plots were similar with regards to growth and quality.

Saskatoon

- There was a lack of moisture throughout the growing season in 2002.
- In 2002 the soil profile was dry at the beginning of the season regardless of pre-planting irrigation. This caused poor seed germination and seedling emergence.
- Most canopies never reached full fill.
- The plots were hand harvested in 2002 due to a cool wet fall that delayed maturity.
- Minor disease incidence was recorded at harvest in 2002.
- In 2003, the trial finished early due to drought, and disease was minimal.

4.2. Yield

The highest yielding adapted genotypes were CDC Plato and CDC Milestone, which yielded higher than either CDC Grandora or Crimson (Table 2). These yield results are supported by the Saskatchewan regional yield trial data that indicate yield advantages for CDC Plato and CDC Milestone of 130 and 136% of the check variety Laird, respectively. Average yields for CDC Grandora and Crimson are reported at only 109 and 118% of the check variety Laird, respectively (Saskatchewan Agriculture and Food, 2003).

Final seed yield of the unadapted genotypes was significantly lower than the adapted genotypes. The highest yielding unadapted genotype, 2000-7L, had nearly half the yield of the lowest yielding adapted genotype Crimson. The low yielding ability of many unadapted genotypes are explained by poor adaptation to daylength and temperature (Whitehead et al., 2000).

Seed yield responded positively to an increase in target plant population, with a steady yield increase from 60 to 140 plants m^{-2}. Wilson and Teare (1972) reported the highest seed yields in lentil were obtained with the highest plant population. Similar results in chickpea reported as high as a 27% yield advantage with increased plant population densities of 20 to 50 plants m^{-2} (Liu et al., 2003). In contrast, Easson et al. (1993) reported a yield reduction in winter wheat with increased seeding rates that were so high as to cause lodging. No yield reduction caused by high plant population was seen in our study, because drought had limited canopy production or delayed canopy closure even in the moistest environments (Vanscoy; Outlook).

4.3. Biomass

Biomass accumulation varied according to genotype (e.g. McPhee et al., 1997) and means are listed in Table 2. CDC Plato and CDC Grandora accumulated the greatest biomass, reflecting their tall and dense bushy growth habit. Unadapted genotypes 96-47L and 2000-6L accumulated the least biomass, while 2000-7L accumulated the greatest biomass of the unadapted genotypes. Crimson had the lowest biomass accumulation of the adapted genotypes, and was not significantly different than 2000-7L. Biomass accumulation tended to increase with the target plant population, although not significant at the $P<0.05$. The greatest biomass accumulation was 505 g m^{-2} at 140 plants m^{-2}.

4.4. Harvest Index

Harvest index values varied greatly between genotypes with an average range of 0.22 to 0.40 (Table 2). Whitehead et al. (2000) found that twelve lentil genotypes had greatly varied harvest index values ranging from 0.07 to 0.56, and concluded that harvest index was largely determined by the genotype and environment. CDC Grandora and CDC Plato had the lowest harvest index values. CDC Grandora and CDC Plato were capable of producing large amounts of vegetative biomass, but were inefficient at further partitioning into seed yield. CDC Milestone had the highest harvest index and represented a very efficient genotype that produced relatively high amounts of vegetative biomass with high seed partitioning. Unadapted genotypes 96-47L and 96-25L had the next highest harvest indices. These genotypes were efficient at partitioning but lacked biomass production and thus seed yield was relatively low compared to the adapted genotypes. Harvest index tended to be consistent

across target plant populations, a finding previously documented in indeterminate and determinate soybean (Ball et al., 2000). We propose that any condition that causes increased vegetative growth, particularly late season growth, will dramatically lower harvest index in an indeterminate crop like lentil.

4.5. Maximum Light Interception by the Canopy

Maximum LI achieved in the growing season differed among genotypes, with a range of 46 to 79% of light intercepted (Table 3). The adapted genotypes had significantly higher maximum LI values than the unadapted genotypes, but the adapted genotypes intercepted only 60% to 80% of the incoming solar radiation. The adapted genotypes were allowing 40 to 20% of incoming solar radiation to pass through the canopy onto the soil surface where it was dissipated as latent heat, used to evaporate soil water, increase weed competition, but was not used by the crop. McKenzie and Hill (1991) found autumn sown lentil in New Zealand were capable of intercepting a maximum of 95% incoming solar radiation. However, when lentil was planted in late spring, the maximum light intercepted was only 65%. In our study, the low maximum LI values may have resulted from the delayed late-May seeding dates resulting in less days to flowering and overall less vegetative growth than early seeded lentil, or the drought conditions reducing overall canopy growth.

CDC Grandora and CDC Plato intercepted the highest proportion of incoming solar radiation, with LI values close to 80%. CDC Milestone and Crimson had the lowest LI values of the adapted genotypes with 68 and 61%, respectively. 2000-7L intercepted a significantly higher portion of incoming solar radiation than the other unadapted genotypes, with an LI value of 56%. 96-47L intercepted the least amount of light, with a maximum LI of only 46%.

Maximum LI differed significantly for target plant populations, with increased LI at the highest plant population. Wilson and Teare (1972) reported similar results where the highest plant densities developed closed canopies and intercepted as much as 90% of incoming solar radiation, whereas the lower plant densities had only partially closed or open canopies and intercepted only about 75 and 47% of the incoming solar radiation, respectively.

4.6. Plant Height and Number of Branches

Pant height and final branch number differed among genotypes (Table 3). Plant height ranged from 0.22 m up to 0.44 m, the tallest genotype being twice the height of the shortest. Erskine and Goodrich (1991) reported significant genotypic differences in twenty-five lentil genotypes for plant height, with a height range of 0.27 to 0.39 m, and significant differences for branch number. CDC Grandora and CDC Plato were the tallest genotypes with heights >0.41 m and had the greatest number of branches with > 19 branches plant^{-1}. CDC Milestone was also tall and highly branched, and ranked third behind CDC Grandora and CDC Plato for both traits. Unadapted genotypes 96-47L and 2000-6L were the shortest, and had the fewest number of branches. 2000-7L was the unadapted genotype with canopy characteristics most closely similar to the adapted genotypes. 2000-7L was the tallest and greatest branched unadapted genotype, and exceeded Crimson for both traits.

Final plant height and branch number both decreased with increased target plant population, but the differences were not significant. Board (2001) reported plant height increased with high plant populations in soybean. Our study found a tendency for branch number to decrease with increased plant population, which has been reported before in lentil (Wilson and Teare, 1972). In soybean, increased branching with reduced plant population is a major reason for yield plasticity, resulting in yields that are generally consistent across a range of plant populations (Board et al., 1990).

4.7. Lodging Score

In our study, lodging scores were highly variable between years (Table 4). In the combined analysis of all locations, genotypes did not differ. When data were analyzed for each year separately, genotypic differences were seen within 2001 and 2002 seasons. In 2001, unadapted genotypes were the most lodging resistant with a range of 7 to 27% plant lodging occurring within the plots. This compares to over 75% plant lodging for CDC Grandora and CDC Plato. CDC Grandora and CDC Plato were bushier and denser than the other genotypes and their stems were unable to withstand the heavy vegetative loads. This was supported by the significant positive correlation of lodging and biomass accumulation (Table 4.12). CDC Grandora and CDC Plato represent the large green lentil class, which tend to grow tall and be susceptible to lodging (Saskatchewan Agriculture and Food, 2001). In 2001, Crimson had the third highest plot lodging with 50% of lentil plants lodged, commonly from

stem basal lodging. In 2001, the stiff stem trait unadapted genotypes combined with increased canopy openness and reduced vegetative load was evident in their low plant lodging scores.

Extreme weather conditions in 2002 caused plant lodging to be highly variable compared to lodging in 2001. In 2002, extreme heat and drought in July followed by frequent rainstorms in August resulted in lentil canopies with reduced biomass accumulation. In previous research on lentil, sufficient vegetative biomass accumulation was required for lodging to occur (Erskine and Goodrich, 1988). The early maturing unadapted genotypes matured in the field during frequent rainstorms, resulting in possible saprophytic stem breakdown for the dry stems, but definitely resulting in stem breakage. The later-maturing adapted genotypes stems were still lush and thus stem breakage did not occur. Grafius et al. (1955) concluded that stem breakage is likely to occur only with senescent plants, as moist and turgid stems rarely break. Therefore, in 2002 the unadapted genotypes lodged the most, and the adapted genotypes the least.

In 2001, lodging increased plant population increased. Ibrahim et al. (1993) reported in lentil that lodging increased with higher plant populations. In 2002, no significant differences for target plant population were found.

Based on the field observations, the 2001 lodging data were most likely to represent true genetic differences for lodging resistance. The unadapted genotypes produced less vegetative biomass, reduced branching, and grew shorter than the adapted genotypes. This resulted in less vegetative canopy load, and combined with the stiff stem trait, these genotypes were better able to withstand lodging. In contrast, the adapted genotypes CDC Grandora and CDC Plato accumulated the greatest vegetative biomass, grew the tallest, were the most branched, and had relatively high seed yields. This resulted in a very dense canopy that made the plants unable to withstand the heavy vegetative load, and stem bending occurred. In 2002, the lodging data were more representative of environmental influence than genetic differences, and timing of the environmental conditions had the greatest influence.

Lodging results are supported by other researchers' findings that lodging is a highly variable trait that is also dependent on environmental conditions. Therefore, determining which plant traits are consistently ranked among genotypes over environments and are highly associated with plant lodging is important. Such ranking permits accurate plant lodging prediction over many years, regardless of weather conditions. Lodging is based on

a visual ranking of the plot, and a more definitive measurement would be more objective and easier to repeat in other experiments.

The highly variable lodging scores reported in this study are similar to those observed in other crops (Mohr and Irvine, 2002; Mancuso and Caviness, 1991). Erskine and Goodrich (1988) grew 242 lentil lines at three locations that varied in rainfall accumulation. Rainfall was limited at one location and no lodging occurred. At the second location, mean lodging scores were similar for the small and large seeded lines, while at the third location, lodging was more severe for the small-seeded lines compared to the large-seeded. Such variation in results across environments support our findings that lodging score is highly variable and inconsistent in lentil, and largely influenced by environmental conditions.

4.8. Recovery from Stem Bending

Due to the inconsistency reported in lodging score for lentil (Erskine and Goodrich, 1988) and other legume crops (eg. Mancuso and Caviness, 1991), looking for plant traits that are associated with lodging score but not highly affected by the environment may lead to more consistent relationships. Indirect selection of lodging resistant lentil could be based on measuring only a few plants early in a breeding program; selection would have limited interference from environmental conditions. The plants ability to recover from stem bending, ability of the canopy to recover from crushing, stem diameter, fiber, and lignin analysis were all measured to determine if these traits showed genotypic differences and if these traits were significantly associated with lodging.

Recovery of plants from stem bending at early pod fill differed according to genotype (Table 5). But the range of recovery angles was small, from 66° to 73° across genotypes. In 2001, recovery from stem bending was performed a second time during the late pod fill growth stage, but adverse weather conditions did not allow the second recovery from stem bending measurements to occur in 2002. The 2001 late pod fill data showed a wider range in recovery angles of 31° to 65°, and again, genotypes differed significantly.

When lodging scores and recovery from stem bending were correlated together either by years or in a combined analysis, no significant association was found. Such contrary associations indicated that recovery for stem bending for lentil was not an effective measurement of lodging resistance in lentil. Plant recovery from stem angle bending performed on four soybean cultivars at the mid vegetative, early pod fill, late pod fill, and pod

maturity (Mancuso and Caviness, 1991). The angle of stem bending was negatively associated with lodging score at the late pod fill and pod maturity stages of development ($P<0.01$), but no significant correlation existed for the mid vegetative and early pod fill development stages.

The stem bending measurements were taken at the beginning of pod fill and may have occurred too early in the plant's development in this study to be an effective lodging predictor. If stem bending measurements were taken closer to full pod fill, they may have been more closely associated with plant lodging.

4.9. Recovery from Canopy Crushing

The ability of canopies to recover from crushing differed according to genotype, with adapted genotypes having the highest percentage of recovery from crushing compared to unadapted genotypes (Table 5). CDC Milestone and Crimson recovered the greatest from canopy crushing, while 96-47L and 2000-6L showed the least ability to recover. Recovery from canopy crushing was thought to be a possible measurement of ability to withstand lodging and would measure stem resiliency. This may be partially true, but it may also be equally representative of maximum biomass accumulation. The adapted genotypes had the greatest biomass accumulation and the greatest ability to recover from canopy crushing. The unadapted genotypes produced lower biomass and recovered less readily from canopy crushing. Genotypes 96-47L and 2000-6L had the lowest biomass accumulation and the lowest ability to recover from canopy crushing with less than 70% recovery. To further support this, recovery from canopy crushing was found to increase, although not significantly, with plant population.

4.10. Stem Diameter or Stem Thickness

The diameter of lentil stems was measured at two positions on the stem: 50 mm above the stem base and at half the plant height (Table 5). Both stem diameter measurements had similar rankings for genotype, thus stem diameter at 50 mm above the stem base alone was the easiest measurement to make and effective. Genotypes had different stem diameters, which has been reported in many other studies (Briggs, 1990; Erskine and Goodrich, 1988: Mancuso and Caviness, 1991). CDC Grandora and CDC Plato had significantly thicker stems than the other genotypes. In general, the unadapted genotypes had slender stems, with 96-47L and 2000-6L producing the thinnest stems. Crimson was the adapted genotype with stem diameter most closely related to the unadapted

genotypes, with stem diameter similar to 96-25L. 2000-7L and CDC Milestone both had similar sizes of stem diameters.

Stem diameter was significantly different for plant population treatments, with a decrease in stem diameter as the plant population increased. Board (2001) and Ibrahim et al. (1993) reported similar results where stem diameter was found to decrease as plant populations moved from low to high in soybean and lentil, respectively.

When lodging score and stem diameter were correlated together, a significant association was observed. Based on the variable weather events between the two years, in 2001 a significant positive association was evident, while in 2002 a significant negative association occurred. The 2001 lodging data were more representative of actual genotypic differences for lodging resistance, and therefore of the eight representative genotypes, the significant positive correlation between lodging susceptibility and stem diameter was more representative of a typical lentil canopy. In general, CDC Grandora and CDC Plato, the large green lentil genotypes, produced the greatest vegetative biomass, grew the tallest, produced the largest diameter stems, and lodged most readily of the genotypes tested. In contrast, Erskine and Goodrich (1988) reported a significant negative association between stem diameter and lodging susceptibility when 25 diverse lentil lines were grown over one season. Woods (1975) and Rode (1972) found lodging decreased as stem diameter increased in soybean. Mancuso and Caviness (1991) reported that basal stem diameter of four soybean cultivars was not significantly correlated with lodging score when measured at four different growth stages. When stem diameter of the eighth internode was measured at the early pod fill, late pod fill, and pod maturity stages of development, only the internode diameter at the pod maturity stage was significantly associated with lodging score. Similar to our results, it suggested a positive association between lodging susceptibility and stem diameter.

4.11. Fiber Analysis of Stems

Both neutral and acid detergent fiber contents were measured, and genotypes differed for NDF and ADF. of the individual genotypes (Table 6). Significant genotypic differences existed for both fiber analyses in our lentil samples, as found in oil-seed rape (*Brassica napus*) and field pea (Travis et al., 1993; Banniza et al., 2003). CDC Grandora, CDC Milestone, and CDC Plato had the highest ADF and NDF. The lowest fiber values were seen in 96-47L and 2000-6L. As population increased, fiber content decreased.

In the combined analysis, fiber content was significantly correlated with plant lodging, but explained less than 22% of the variation in lodging. In 2001, both NDF and ADF were significantly and positively correlated with lodging, explaining approximately 50% of lodging variation. In 2002, the variable weather events and the effect on lodging data resulted in no correlations between NDF and ADF with lodging scores. Banniza et al. (2003) found the fiber content of field pea increased pea lodging decreased in a narrower range of commercial cultivars. In our lentil study, as fiber increased, lodging increased. The significant positive association between lodging score and fiber content may be the result of higher fiber content in the stems of the large green lentil varieties that grow the tallest, develop the most branches, and produce the greatest biomass, and thus lodge more readily. Lentil is very different in plant shape than semi leafless and leafless pea cultivars. Therefore, the higher fiber content of the genotypes most susceptible to lodging in this study may be the result of greater overall plant size. In oil-seed rape, fiber content was significantly higher in the variety less susceptible to lodging (Travis et al., 1993). In soybean, the cultivars that lodged most severely had lower NDF contents in their stems, thus causing reduced cellulose content (Redfearn et al., 1999). Kokubo et al. (1989) reported in barley stems that a higher cellulose content was related to a greater maximum bending stress to cause lodging, and reduced lodging.

Lignin content of plant stems was analyzed, but genotypic differences were not significant. Travis et al. (1996) found wheat varieties varying in lodging resistance were not associated with differences in lignin content. As population increased, lignin content decreased. Lignin content was found to have a significant and positive association with lodging susceptibility in the combined analysis, 2001, and 2002. However, the 2001 association explained the highest proportion of lodging variability at only 46%. In field pea, a negative association between lignin content and lodging was reported (Banniza et al., 2003).

4.12. Pair-wise Comparisons among Measurement Variables

Lodging score was found to be correlated with only maximum biomass, recovery from crushing, NDF, ADF, and ADL in the combined analysis (Table 7). None of these correlation values were greater than 0.5, probably due to the adverse weather conditions as explained previously. Correlations for lodging score performed by year resulted in everything being significant except for recovery from stem bending in both years, and NDF and ADF in 2002. Stem diameter and final plant height were the only canopy characteristics that had correlation

values with lodging >0.5 over both years. These two traits appeared to be the most influential on lodging of the plant canopy characteristics measured.

The plant traits associated with lodging were correlated against the same canopy characteristics that were used with lodging score (Table 8). In the combined analysis, many of the correlations were significant, but few correlations produced values of r>0.5. Simple linear regressions were then performed in the same combinations as the above correlations. Lodging score regressed against final plant height in 2001 gave an R^2 of 0.52. However, this was the only trait that could explain over 50% variation in lodging, therefore, not any one single trait could explain a high proportion of the lodging variability. Similar results were found when the plant traits associated with lodging were regressed against the canopy characteristics. Stem diameter regressed against plant height could explain >50% of stem diameter variability. NDF, ADF, and ADL, being inter-related measurements, were found to explain a high variability among those traits with 80% or more as expected.

4.13. Combining Numerous Measurement Variables by Multiple Regression

No single canopy measurement could explain a high proportion of the variability for lodging. Multiple linear regression was then used to group more traits in an attempt to better explain the variability in lodging. Multiple linear regressions were performed for independent variables (Y) of lodging score and stem diameter. Stem diameter was the only plant trait associated with lodging that was further used in the multiple linear regressions. The reason was that it was the only trait associated with lodging that had correlation values >0.5 for both years and explained the highest proportion of lodging variability in both 2001 and 2002 of the plant traits associated with lodging. Therefore, stem diameter was believed to be the most influential trait associated with lodging.

Findings from multiple linear regressions showed that the R^2 increased compared to when we used simple linear regressions for both lodging score and stem diameter (Table 9). Lodging score in the multiple linear regressions had adjusted R^2 values of 0.24, 0.60, and 0.40 for the combined, 2001, and 2002 analyses, respectively. Stem diameter in the multiple linear regressions produced higher R^2 values than lodging score, with R^2 values of 0.67, 0.78, and 0.62 for the combined, 2001, and 2002 analyses, respectively. The high R^2 for stem

diameter in the combined analysis indicates that stem diameter may be a better measurement than lodging as a higher proportion of variability in stem diameter could be explained over years.

The variables that were found to affect stem diameter were final branch number, recovery from canopy crushing, plant density, final plant height, NDF, ADF, and ADL.

4.14. Genotypic Differences in Canopy Architecture

The genotypes used in this study varied significantly for both agronomic performance and canopy characteristics. CDC Plato and CDC Grandora were representative of late-maturing large green lentil varieties. CDC Plato and CDC Grandora accumulated the greatest above ground biomass, grew the tallest, and had the most branches. These characteristics resulted in a denser and taller canopy growth than the other genotypes studied and allowed the highest percentage of incoming solar radiation to be intercepted. However, CDC Plato and CDC Grandora lodged the most readily in 2001 and had the lowest mean harvest index values. Despite high plant lodging and low harvest indices, CDC Plato and CDC Grandora had good yield.

CDC Milestone is somewhat more efficient in growth, effectively partitioning biomass to yield, and is an impressive genotype from a canopy perspective. CDC Milestone was the second highest yielding genotype and had the highest harvest index. CDC Milestone ranked third behind CDC Plato and CDC Grandora for the following traits: biomass accumulation, maximum light interception, plant height, and final branch number. In 2001 CDC Milestone lodged the least of the adapted genotypes. Overall, CDC Milestone was high yielding with smaller canopy growth compared to CDC Plato and CDC Grandora, but was more efficient at partitioning and lodged less readily than either CDC Plato or CDC Grandora. Reduction in above ground dry matter in the large green lentil market class may lead to increased lodging tolerance by reducing plant branch number or height. However, lentil is already a short plant and further reduction in height is generally not recommended except in the large green lentil market class (Laird, CDC Grandora). Therefore, reduction in the amount of biomass produced by the canopy, particularly in late season branching, should occur without the reduction in plant height, and harvest index can be increased.

Crimson was the poorest performing adapted genotype, with the lowest values for seed yield, biomass accumulation, and maximum light interception of the adapted genotypes. Crimson grew shorter than 2000-7L and had fewer branches than both 2000-7L and 96-25L. Crimson did have a higher harvest index and lodged less

compared to both CDC Plato and CDC Grandora - presumably the lower yield performance in Saskatchewan is due to the plant not growing enough.

2000-7L performed the best of the unadapted genotypes. 2000-7L yielded less than the adapted genotypes, but higher than the other unadapted genotypes. 2000-7L had a higher harvest index than either CDC Grandora or CDC Plato, and was not significantly different than Crimson. 2000-7L accumulated greater biomass, grew taller, and had more branches than the other unadapted genotypes. In 2001, 2000-7L was the second most lodging resistant genotype, behind only 96-47L. Of the unadapted genotypes, 2000-7L had the thickest and tallest canopy and was superior for yield, harvest index, and lodging.

96-47L, 2000-6L, and 96-25L were the lowest yielding genotypes, accumulated the least biomass, and intercepted the least incoming solar radiation. 96-47L and 2000-6L were the shortest and least branched. However, 96-47L had a higher harvest index than Crimson, CDC Grandora, and CDC Plato and was the most lodging resistant genotype in 2001, making it a good candidate for a stiff stemmed parent but with lower yield.

4.15. Disease Incidence

Disease incidence was analyzed for three representative environments in the study: Saskatoon 2002 which had a wet end-of season where disease expectation was the greatest, and the high yielding disease and control sets of irrigated plots at Outlook in 2002. For Saskatoon, *Ascochyta* was present at very low levels in most plots, *Anthracnose* was present in 10% of the plots (ICARDA lines, CDC Milestone and Crimson), but no *Scerotinia* or *Botrytis* was seen. As plant population increased from 60 to 140 plants m^{-2}, disease increased from 0.2 to 1.1 on a scale of 0 to 9; statistically significant but of no practical significance. 2000-7L was the most susceptible genotype to *Ascochyta* with a mean rating of 1.2 compared to the experimental mean of 0.8. At Outlook, low levels of *Ascochyta* only were seen in <40% of the control plots, and almost all the disease plots. For the Outlook control plots, disease was 0.6 on a 0 to 9 scale, which was not statistically significant. Genotypes and plant population densities did not affect disease incidence but 2000-7L, the most bushy ICARDA genotype, had a higher rating of 1.1 compared to the average of 0.6. In the disease plots, 2000-7L had the higher rating of 1.8 compared to the average of 1.4. Certainly, for the population ranges used in the study, high population does not create canopy conditions that cause significant increases in *Ascochyta* or other disease in average to dry years.

4.16. Color Analysis

Poor seed from combine harvested samples taken from two environments, high yielding Vanscoy and low yielding Rosthern, was separated by visual grading - any seed with wrinkles, cracks, disease lesions, and immatures. The percentage of poor seed found was determined by genotype in both environments, not by increasing plant population density. For Rosthern, two ICARDA genotypes, 2000-6L and 96-47L had 4.2 and 4.5% poor seed, higher than the range of 1.8 to 2.7% for the other genotypes. The same pattern of treatment effects was seen at Vanscoy, with four genotypes having a greater percentage of poor seed. These were 2000-6L (5.0%), 96-47L (4.0%), CDC Grandora (5.1%), and CDC Plato (3.8%), compared to the other genotypes with less than 2.6% poor seed.

5. Conclusions

The results of this study indicate that lodging is a very complex trait and the lentil genotypes that accumulate the greatest above ground biomass, yield the highest, grow the tallest, and branch the most are more likely to lodge the most. In our research, plant lodging was highly influenced by both genetic differences among the genotypes and environmental conditions. The environmental influence makes selection for lodging resistance very difficult because a genotype that may show resistance to lodging in one year, may be very susceptible the following year. The greater the fiber content in the plant stems (ADF, NDF), the more biomass and, surprisingly, the more likely lodging is to occur. Lignin (ADL) was more difficult to interpret. Fiber was linked to biomass and does not appear to be an effective trait to measure for lodging resistance in lentil, at least in a diverse group of genotypes as represented in this study.

Stem diameter was not the only influence on the variability found in plant lodging. The most influential variables on plant lodging were: recovery from canopy crushing, stem diameter, final plant height, NDF, and ADF. However, a single plant trait, stem diameter, associated with lodging could be used to select for lodging resistance in lentil. Genotype ranking for stem diameter was found to be consistent from year to year, and regardless of the position on the plants stem it was measured. Therefore, determining the largest from the smallest stem diameters should be relatively simple and more consistent than lodging score, and would allow selection for lodging tolerance early in a breeding program based on only a few plants.

6. Recommendations

- Most stiff stemmed parent for crossing: FLIP 95-47L, but has lower yield.
- Good stiff stemmed and highest yielding parent for crossing: FLIP 2000-7L.
- Increasing the plant population density of lentil from 100 m^{-2} (1, 000, 000 ha^{-1}) to 140 m^{-2} (1, 400, 000 ha^{-1}) will improve yield potential in dry years (Table 10). Note: this recommendation is from data in this report only, where up to 15% of the target population failed to emerge at many locations.
- In moist conditions, no yield penalty occurs with high plant population densities, although *Ascochyta* disease increased slightly from 0.6 to 1.4 on a 0 (no disease) to 9 (dead plant) scale. No significant increase in other diseases (*Anthracnose*, *Sclerotinia*, *Botrytis*) was found.
- FLIP 2000-7L is marginally more susceptible to *Ascochyta* than the other FLIP genotypes in this report (1.2 compared to 0.4, adapted cultivars were between 0.6 and 0.9).
- The data used in this report are from dryer than normal environments, with the exception of Briercrest.

Table 10. Performance of adapted lentil to increasing plant population in three Saskatchewan soil zones. (To convert population to plants ha^{-1} or yield to kg ha^{-1} multiply by 10,000 or 10, respectively.)

Soil Zone	Location	Target population (plants m^{-2})	Yield (g m^{-2})
black	Rosthern	60	86
black	Preston	60	126
black	Rosthern	100	136
black	Preston	100	144
black	Rosthern	140	144
black	Preston	140	147
brown	Briercrest	100	48
brown	Briercrest	60	50
brown	Briercrest	140	50
brown	Outlook	100	172
brown	Outlook	60	191
brown	Outlook	140	195
moist dark brown	Vanscoy	60	153
moist dark brown	Vanscoy	100	206
moist dark brown	Vanscoy	140	252
Meaned over plant population density for each location			
black	Rosthern	100	122
black	Preston	100	139
brown	Briercrest	100	49
brown	Outlook	100	186
moist dark brown	Vanscoy	100	204

7. Work in Progress

Crosses have been made between CDC Milestone and several FLIP lines to incorporate the stiff stem trait. Breeding is in progress to select the best adapted progenies from these crosses for Saskatchewan. A quantitative Trait Loci study for heritibility of the stiff stem trait was started in winter 2001 in the phytotron using single seed descent.

8. Information of Benefit to Producers

Progress of this work has been presented as posters at the following meetings and conferences: North American Pulse Improvement Association Annual Meetings, Fargo, N. Dakota, USA, October 2001; North American Pulse Improvement Association Annual Meetings, Sacramento, California, USA, October 2003; Agronomy Society of America Annual Meetings, Denver, November 2003. Pulse Days in Saskatoon, January 2002, 2003 and 2004. Soils and Crops, March 2003 in Saskatoon.

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EQUIPMENT

Rental of University of Saskatchewan field equipment.

PROJECT DEVELOPED MATERIALS

None to date.

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TABLES 1 to 9

Table 1. Average monthly temperatures (°C) and cumulative precipitation (mm) for Rosthern, Vanscoy, Outlook, Briercrest, and Saskatoon, Saskatchewan for the two years of the study on which the technical report is based.

		June	July	August
Average Temperature				
2001	Rosthern	15.6[z]	19.6	19.9
2001	Vanscoy	15.5[y]	19.7	19.8
2002	Outlook	17.1	20.4	16.7
2002	Briercrest	16.7	20.8	17.0
2002	Saskatoon	17.3	20.1	16.6
Average[x]	Saskatoon	16.0	18.3	17.6
Average[x]	Moose Jaw	17.1	19.4	18.6
Monthly Precipitation				
2001	Rosthern	49.0[z]	66.1	10.5
2001	Vanscoy	38.3[y]	52.2	6.0
2002	Outlook	64.4	22.8	56.6
2002	Briercrest	167.8	37.4	105.5
2002	Saskatoon	52.2	69.5	75.2
Average[x]	Saskatoon	60.5	57.3	35.4
Average[x]	Moose Jaw	60.2	57.3	39.8

[z] Environment Canada measurements for Langham
[y] Environment Canada measurements for Saskatoon
[x] Long term average from Environment Canada (2004)

Table 2. Effects of genotype and target plant population treatments for seed yield, harvest index, and maximum biomass accumulation in lentil, for data combined over all the data.

	Seed Yield ($g\ m^{-2}$)	Harvest Index	Maximum Biomass Accumulation ($g\ m^{-2}$)
Genotype			
2000-6L	35 c [z]	0.30 cd	376 ef
2000-7L	53 b	0.32 bc	476 d
96-25L	36 c	0.36 ab	386 e
96-47L	24 d	0.35 b	328 f
CDC Grandora	106 a	0.22 e	669 ab
CDC Milestone	113 a	0.40 a	597 bc
CDC Plato	127 a	0.26 de	697 a
Crimson	96 a	0.34 bc	525 cd
LSD	0.339[y]	0.05	0.148[y]
Target Plant Population			
60 pl m^{-2}	51 b	0.32 a	468 a
100 pl m^{-2}	64 a	0.32 a	497 a
140 pl m^{-2}	74 a	0.32 a	505 a
LSD	0.187[y]	0.01	0.083[y]

[z] Means within columns and groups followed by the same letter are not significantly different according to Tukey's test at $P \leq 0.05$.

[y] Untransformed LSDs using logarithmic transformation on seed yield and biomass accumulation.

Table 3. Effects of genotype and target plant population treatments for maximum light interception, final plant height, and final branch number in lentil, for data combined over all the data.

	Maximum Light Interception (%)	Final Plant Height (m)	Final Branch Number
Genotype			
2000-6L	50 e [z]	0.235 de	16.5 d
2000-7L	56 d	0.293 b	18.2 bc
96-25L	51 e	0.254 cd	17.3 cd
96-47L	46 f	0.221 e	16.2 d
CDC Grandora	79 a	0.436 a	19.1 ab
CDC Milestone	68 b	0.301 b	18.5 ab
CDC Plato	78 a	0.413 a	19.5 a
Crimson	61 c	0.281 bc	17.1 d
LSD	4	0.030	1.1
Target Plant Population			
60 pl m^{-2}	56 b	0.310 a	18.0 a
100 pl m^{-2}	62 a	0.306 a	17.8 a
140 pl m^{-2}	64 a	0.298 a	17.6 a
LSD	3	0.014	0.6

[z] Means within columns and groups followed by the same letter are not significantly different according to Tukey's test at $P \leq 0.05$.

Table 4. Effects of genotype and target plant population treatments for lodging score in lentil, for data combined over all data followed by 2001 and 2002 separately.

	Combined	2001	2002
Genotype			
2000-6L	4.4 a[z]	2.7 c	5.0 bc
2000-7L	3.6 a	1.6 d	4.5 cd
96-25L	4.9 a	2.1 cd	6.0 ab
96-47L	5.0 a	0.7 e	6.8 a
CDC Grandora	4.2 a	8.1 a	2.7 e
CDC Milestone	4.0 a	4.5 b	3.8 de
CDC Plato	4.3 a	7.6 a	3.0 e
Crimson	4.6 a	4.9 b	4.5 cd
LSD	2.2	0.8	1.2
Target Plant Population			
60 pl m^{-2}	4.5 a	3.8 b	4.7 a
100 pl m^{-2}	4.3 a	3.9 ab	4.4 a
140 pl m^{-2}	4.4 a	4.3 a	4.5 a
LSD	0.4	0.4	0.6

[z] Means within columns and groups followed by the same letter are not significantly different according to Tukey's test at $P \leq 0.05$.

Table 5. Effects of genotype and target plant population treatments for recovery from stem bending, recovery from canopy crushing, stem diameter at 50 mm, and stem diameter at half plant height in lentil, combined over all data.

	Recovery from Stem Bending (°)	Recovery from Canopy Crushing (%)	Stem Diameter at 50mm (mm)	Stem Diameter at Half Height (mm)
Genotype				
2000-6L	72.6 a [z]	68.5 d	1.23 de	0.99 e
2000-7L	67.2 bc	72.3 bcd	1.54 c	1.09 cd
96-25L	68.0 bc	72.2 cd	1.35 d	1.05 d
96-47L	70.1 ab	69.6 d	1.17 e	0.92 f
CDC Grandora	68.1 bc	76.2 abc	2.07 a	1.35 a
CDC Milestone	67.8 bc	77.4 a	1.59 c	1.12 c
CDC Plato	68.2 bc	75.3 abc	1.92 b	1.29 b
Crimson	65.6 c	76.3 ab	1.34 d	1.05 de
LSD	4.0	4.0	0.14	0.06
Target Plant Population				
60 pl m^{-2}	69.6 a	72.4 a	1.61 a	1.14 a
100 pl m^{-2}	67.1 a	73.4 a	1.49 b	1.10 ab
140 pl m^{-2}	67.9 a	74.6 a	1.47 b	1.09 b
LSD	2.5	2.4	0.11	0.05

[z] Means within columns and groups followed by the same letter are not significantly different according to Tukey's test at $P \leq 0.05$.

Table 6. Effects of genotype and target plant population treatments for neutral detergent fiber, acid detergent fiber, and acid detergent lignin concentration in lentil stems, for data combined over all data.

	Neutral Detergent Fiber (%)	Acid Detergent Fiber (%)	Acid Detergent Lignin (%)
Genotype			
2000-6L	55.1 d [z]	41.5 b	10.3 b
2000-7L	59.0 abcd	44.8 ab	11.1 ab
96-25L	59.3 abcd	45.5 a	11.5 ab
96-47L	55.8 cd	41.2 b	10.2 b
CDC Grandora	62.0 a	47.7 a	11.4 ab
CDC Milestone	61.2 ab	47.1 a	11.6 a
CDC Plato	60.2 abc	46.0 a	11.2 ab
Crimson	57.2 bcd	43.9 ab	11.3 ab
LSD	4.3	3.8	1.3
Target Plant Population			
60 pl m^{-2}	60.0 a	45.7 a	11.4 a
100 pl m^{-2}	58.6 ab	44.7 ab	11.0 ab
140 pl m^{-2}	57.6 b	43.7 b	10.8 b
LSD	1.6	1.0	0.5

[z] Means within columns and groups followed by the same letter are not significantly different according to Tukey's test at $P \leq 0.05$.

Table 7. Pearson correlation coefficients and probability values correlated between lodging score and ten plant canopy characteristics for eight lentil genotypes in 2001, 2002, and both years combined.

	2001	2002	Combined analysis
Maximum BM[z]	0.539 (<.001)	-0.439 (<.001)	-0.096 (0.037)
Maximum LI[y]	0.533 (<.001)	-0.496 (<.001)	-0.087 (0.056)
Final branch number	0.366 (<.001)	-0.436 (<.001)	-0.081 (0.078)
Final plant height	0.724 (<.001)	-0.592 (<.001)	-0.006 (0.895)
Stem bending	0.043 (0.559)	0.008 (0.887)	0.034 (0.457)
Recovery from crushing	0.464 (<.001)	-0.130 (0.028)	0.092 (0.045)
Stem diameter	0.572 (<.001)	-0.508 (<.001)	-0.039 (0.396)
NDF[x]	0.476 (<.001)	0.106 (0.076)	0.213 (<.001)
ADF[w]	0.502 (<.001)	0.087 (0.146)	0.212 (<.001)
ADL[v]	0.461 (<.001)	0.151 (0.011)	0.230 (<.001)

[z] BM is biomass
[y] LI is light interception
[x] NDF is neutral detergent fiber
[w] ADF is acid detergent fiber
[v] ADL is acid detergent lignin

Table 8. Pearson correlation coefficients and probability values correlated between plant traits associated with lodging and ten plant canopy characteristics for eight lentil genotypes for data combined over all data.

	Maximum BM	Maximum LI	Final branch number	Final plant height	Stem bending	Recovery from crushing	Stem diameter	NDF	ADF	ADL
Stem bending	-0.134 (0.004)	-0.225 (<.001)	-0.066 (0.150)	-0.150 (0.001)	-	0.122 (0.008)	-0.167 (0.001)	-0.142 (0.002)	-0.180 (<.001)	-0.101 (0.029)
Recovery from crushing	0.396 (<.001)	0.324 (<.001)	0.313 (<.001)	0.175 (0.001)	0.122 (0.008)	-	0.125 (0.007)	-0.299 (<.001)	-0.284 (<.001)	-0.310 (<.001)
Stem diameter	0.476 (<.001)	0.424 (<.001)	0.483 (<.001)	0.774 (<.001)	-0.167 (0.001)	0.125 (0.007)	-	0.216 (<.001)	0.232 (<.001)	0.140 (0.002)
NDF	-0.101 (0.030)	-0.021 (0.643)	-0.052 (0.262)	0.221 (<.001)	-0.142 (0.002)	-0.299 (<.001)	0.216 (<.001)	-	0.981 (<.001)	0.891 (<.001)
ADF	-0.049 (0.295)	0.038 (0.411)	-0.044 (0.339)	0.249 (<.001)	-0.180 (<.001)	-0.284 (<.001)	0.232 (<.001)	0.981 (<.001)	-	0.898 (<.001)
ADL	-0.139 (0.003)	-0.106 (0.021)	-0.085 (0.065)	0.135 (0.004)	-0.101 (0.029)	-0.310 (<.001)	0.140 (0.002)	0.891 (<.001)	0.898 (<.001)	-

Table 9. Multiple linear regressions for lodging score and stem diameter for combined analysis and years 2001 and 2002.

Y Variable	X Variables	Analysis	Adjusted R^2
Lodging Score	Recovery from Canopy Crushing, NDF, ADF, Stem Diameter, Final Plant Height	All Environments Year 2001 Year 2002	0.24 0.60 0.40
Stem Diameter	Final Branch Number, Recovery from Canopy Crushing, Plant Density, Final Plant Height, NDF, ADF, ADL	All Environments Year 2001 Year 2002	0.67 0.78 0.62
Stem Diameter/ADL	Recovery from Canopy Crushing, Plant Density, Final Plant Height, NDF, ADF, Recovery from Stem Bending	All Environments Year 2001 Year 2002	0.65 0.62 0.66
Stem Diameter/ADF	Recovery from Canopy Crushing, Final Branch Number, Final Plant Height, Plant Density, NDF, ADL	All Environments Year 2001 Year 2002	0.65 0.60 0.66